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Evaluation of Compact Heat Exchanger Technologies for Hybrid Fuel Cell and Gas Turbine System Recuperators

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Abstract

Hybridized Carbonate and Solid Oxide fuel cell power plants are currently under investigation to fulfill demands for high efficiency and low emissions. Selection of high performance, compact recuperators is essential for such applications. In this paper compact heat exchanger (CHEX) technology applicable to hybrid fuel cell and gas turbine technology has been extensively reviewed. Various compact heat exchanger designs pertinent to gas-gas recuperative duties for fuel cell and gas turbine (FCGT) hybrid systems are presented. The type of CHEXs considered in this study included: brazed plate-fin, fin-tube, microchannel, primary surface and spiral. Comparison of the candidate designs is performed by rating each exchanger with a set of desired criteria. Based on this rating procedure, two CHEX designs namely, plate-fin and microchannel were chosen for further review. Plain, strip, louver, wavy and semicircular surface geometries were then analyzed with a numerical CHEX sizing procedure ultimately to select the most suitable surface geometry for FCGT systems. The brazed plate-fin CHEX having the louver fin geometry was chosen, where numerical results show that this surface holds the greatest potential for CHEX size and cost reduction.

1. Introduction

Fuel cell technology has been identified to meet simultaneous demands for more electric power and less pollution. In particular, high temperature fuel cells can utilize existing natural gas infrastructures effectively. Carbonate and Solid Oxide fuel cells operate at high temperature and reject a significant amount of heat so that hybridized fuel cell and gas turbine (FCGT) power plants are under investigation. Ultra high fuel to electricity conversion efficiency (>70% LHV) of such designs is projected.

Recuperator design is instrumental to the success of a hybrid FCGT power plant. A recuperator with low effectiveness will have a large impact on system cost with only minimal impact on system output, and similarly, a recuperator with very high effectiveness will have a large size so that it will be too expensive to make the best overall impact, Utriainen and Sunden [1]. In addition, fuel cell systems have much lower power density than competing gas turbine systems. Therefore, component size is a principle issue for the FCGT hybrid design, especially since distributed power stations will likely have demand in areas where space is limited.

2. CHEX Technology Review

Compact heat exchangers offer the ability to transfer heat between large volumes of gas with minimum footprint. The degree to which an exchanger is considered compact can be characterized by the compactness parameter (β). A gas to fluid exchanger is considered compact if it has a heat transfer area to volume ratio (β) greater than 700 m^2/m^3 on at least one of the fluid sides, Shah [2]. Compactness is a good indication of performance, the higher the compactness generally the higher the effectiveness for a given pressure drop, Oswald [3].

2.1 Brazed Plate-Fin Exchangers

Compact brazed plate-fin exchangers (BPFE) have a long history in gas-gas heat transfer applications because of their ability to achieve high levels of compactness. An illustration of a generic counterflow plate-fin exchanger is shown in Fig. 1. There are numerous surface geometries that can be used in BPFEs. Offset strip-fins have more than 60 years of research behind them and are commonly employed. Louver fins are also widely used given their mass production manufacturability.

Nomenclature

a	Parting plate thickness, (m)
A	Total heat transfer area, $NTUC_{min}/U$, (m^2)
A_{fr}	Frontal area, A_o/σ, (m^2)
A_o	Minimum free flow area, m_{dot}/G, (m^2)
A_r	Fin area per total area, (---)
b	Plate spacing, (m)
C	Heat capacity rate, (W/K)
D_h	Hydraulic diameter, $4A_oL/A$,(m)
f	Fanning friction factor, (---)
g_c	Force-mass conversion constant
G	Mass velocity, (kg/m^2*s)
h	Convective heat transfer coefficient, $jGC_pPr^{(-2/3)}$, (W/m^2*K)
j	Colburn factor, (---)
k	Thermal conductivity, (W/m*K)
l	Fin length, (m)
L	Core length, $D_hA/4A_o$, (m)
m_{dot}	Mass flow rate, (kg/s)
NTU	Number of heat transfer units, (---)
ntu	Number of heat transfer units based on one fluid side, $\eta_o hA/C$, (---)
ΔP	Pressure drop, (kPa)
Pr	Prandtl number, (---)
Q	Exchanger heat duty, (kW)
Re	Reynolds number, GD_h/μ, (---)
TD	Exchanger thermal density, Q/V, (MW/m^3)
U	Overall heat transfer coefficient, (W/m^2*K)
V	Exchanger volume, A/α, (m^3)

Greek Symbols

α	Ratio of total heat transfer area on one side of an exchanger to the total volume of the exchanger, (m^{-1})
β	Compactness, ratio of heat transfer area on one side of a heat exchanger to the volume between the plates on that side, (m^2/m^3)
ε	Heat exchanger effectiveness
η_f	Fin efficiency, (---)
η_o	Extended surface efficiency, $1-A_r(1-\eta_f)$, (---)
ρ	Fluid density, (kg/m^3)
σ	Ratio of free flow area to frontal area, (---)
μ	Dynamic viscosity, (cp)

Subscripts

c	Cold fluid side
h	Hot fluid side
i	Inlet
o	Outlet
s	Scale
w	Wall
1	One section of the exchanger
2	Other section of the exchanger

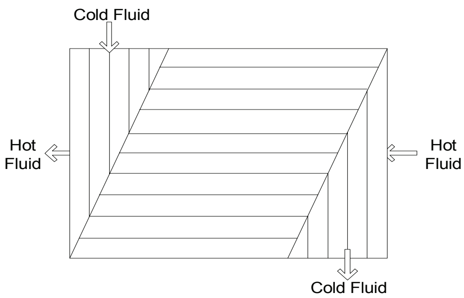

Fig. 1. Counterflow Plate Fin Heat Exchanger

A BPFE relevant to high temperature operation is available from Ingersoll-Rand. The design has a minimal need for preload and is modular, where cells and cores can be stacked together to meet a desired heat load. Five different cell sizes are available, including three different plate areas and two different fin heights, Kesseli et al. [4].

2.2 Fin-Tube Exchangers

Compact fin-tube exchangers (FTE) can consist of various tube, fin, and flow orientations where generally, small bore tubes are spaced closely together. Bare tube bundles in counterflow represent one of the first gas turbine recuperator designs manufactured over 40 years ago by Escher-Wyss, Ltd., Fraas and Ozisik [5]. The performance of this bulky design was improved by adding longitudinal fins; however, the improved design was still far from compact. Escher-Wyss used filler shapes to block gas flow through the interstices of the tube bundles and at the center of each tube in an attempt to provide fluids with sufficient proximity with exchanger surfaces.

Small bore, oval shaped tubes are good for pressure containment and can exhibit structural integrity in a cyclic environment. However, tubular structures are generally not amenable to a modular design approach. Tubes also have poor thermal density and are expensive compared to sheets. Use of tubes is rarely warranted for high temperature, low pressure, gas-gas operation.

2.3 Microchannel Exchangers

Microchannel exchangers are classified by having hydraulic diameter between 10 and 200 μm and minichannel exchangers having hydraulic diameter between 200 to 3000 μm, Kandlikar and Grande [6]. However, this work will consider microchannel exchangers (ME) as those fabricated from individual flat plates having high compactness. In addition, MEs fabricated specifically by chemical etching will be further classified and referred to as printed circuit heat exchangers (PCHE).

It has been reported that MEs can experience unexpectedly high heat transfer performance, Reid [7]. It is said that surface roughness is a main parameter of this, which could represent an easily acquired and economical way to pursue CHEX performance enhancement. Despite this understanding there is still much difficulty in correlating numerical predictions with experimental data in MEs, so that uncharted and perhaps risky territory exists in this area. A commercial PCHE anticipated suitable for gas-gas exchange is fabricated by Heatric Ltd. Plates in Heatric's exchanger are diffusion bonded so that the connections are said to be as strong as the parent metal. However, it is yet to be seen how conducive this technology is with high temperature nickel alloys.

2.4 Primary Surface Exchangers

Primary surface exchangers (PSE) are characterized by having only a primary surface to transfer heat between fluid streams; there are no secondary surfaces (fins). Solar Turbines Inc. has developed this type of recuperator for over 30 years. They report that clamping cells together, instead of having a rigid cell structure, can permit enough movement between cell contacts to relieve concentrated stresses at weld locations. Sound suppression is also attributed to the damping characteristic of the clamped design, Solar Turbines [8].

However, stamped plate PSE designs are compactness limited and folded sheet PSE designs can suffer from exhaust flow blockage due to a lack of support structures between cells. The latter consideration is a very important aspect for high temperature (>650°C) operation. Another disadvantage of the PSE design is that they can require a significant preload mechanism which can result in complex and expensive manufacturing procedures, Kesseli [4].

2.5 Spiral Exchangers

Spiral exchangers (SE) have traditionally been used with particle laden or high viscosity fluids because of their self-cleaning nature. Scale is swept away from turbulence induced by swirling fluid paths. A fouling factor of one third that of shell and tube type exchangers is not unusual for SEs. Mechanical cleansing is also a desirable alternative available with some of the spiral designs. However, SEs generally have low compactness. In addition, the coiled design can require extensive manufacturing equipment. However, the SE is currently in development and has been proposed by Oswald [3] to withstand the structural problems of gas turbine recuperators.

2.6 CHEX Summary

Based on the emphasis that smaller core volume and increased performance can be obtained by increasing compactness, it was determined that this criterion is very important for the FCGT application. Therefore, an extensive literature review was conducted to estimate a range of compactness for each CHEX and tabulated in Table 1.

Table 1. Compactness Range

Exchanger Type	Compactness (m^2/m^3)
Plate-Fin	250 – 6560
Fin-Tube	190 - 3300 / Fin
	138 - 1150 / Tube
Microchannel	2000 - 10,000
Primary Surface	1640 – 3600
Spiral	120 – 1600

Complete detail of numerous BPFE and FTE surface configurations were found in the extensive work of Kays and London [9]. The BPFE was found to have compactness figures of up to 6560 m^2/m^3, given by Kraus et al. [10]. Compactness data for the FTE was found to have up to 3300 m^2/m^3 although for crossflow orientation. Data for counterflow FTEs with longitudinal fins could not be found since they are generally not even considered compact, Shah and Webb [11]. The tube side of the FTE displays rather low compactness, reaching only 1150 m^2/m^3, Shah [12]. The ME is discussed in Wadekar [13] and Hesselgreaves [14]. The PSE was found to have a compactness range of 1640 to 3600 m^2/m^3 by Utriainen and Sunden [15] and McDonald [16] respectively. The SE data was found to max out at 1600 m^2/m^3, Bacquet [17].

2.7 Durability

Historically, gas turbine recuperators have had very poor reliability due to fatigue and creep problems. Although, temperature ramping is expected to be much slower for FCGT systems, where high temperature fuel cells generally have a much longer start up time and more gradual transients than do traditional gas-fired turbine systems. However, some FCGT recuperators may be used for load leveling and or quick startup, where they could be subject to stringent temperature ramping rates. This scenario would most likely place durability as the primary design constraint as it is with traditional gas turbine recuperators. Despite this concern it is assumed that most FCGT systems will not operate in this manner, and that the temperature ramping rate in the recuperators will follow closely to that of the fuel cells. Therefore, durability requirements are considered not as severe for the present application.

2.8 Fouling and Corrosion

Fouling is one of the major potential problems in compact heat exchangers due to small hydraulic diameter and lack of cleaning ability. Fouling can reduce the heat transfer coefficient 5 to 10 percent in general, but can increase the pressure drop up to several hundred percent, particularly for compact heat exchangers with gas flow, Shah [2]. Fouling mechanisms are in general understood, but little success has been made in prediction and prevention. Effective cleaning techniques will be an increasingly important requirement for CHEX design.

It has been reported that water vapor has a deleterious role on the oxidative lifetime of metallic recuperators, Pint et al. [18]. This is important for FCGT recuperators where process streams have relatively high steam content. Corrosion processes can be reduced by utilizing nickel bearing alloys which can provide general corrosion resistance and maintain sufficient mechanical properties. However, when a heat exchanger has to be made from an expensive nickel alloy, the cost of raw material generally dominates the cost of the exchanger, Deakin et al. [19].

2.9 Cost

High compactness is desired for FCGT recuperators, although increased compactness will generally reflect in increased capital cost. For a given pressure drop, the higher is the compactness, shorter is the flow length and larger is the frontal area. This implies that higher compactness yields smaller plate size, resulting in more plates and higher fabrication cost. However, higher compactness generally yields higher CHEX performance, so that a trade off is expected. Market availability is expected to be a heavy proponent for the high temperature (>650°C) application, where use of nickel alloys is usually warranted. BPFE cost has been well documented in Kesseli et al. [4].

3. Performance Comparison Method

The two step heat exchanger selection approach outlined by Wadekar [13] was used in this procedure. The first step consists of a coarse filter elimination, where CHEX types are compared and most of which eliminated. The second step consists of a fine filter elimination, where different surface geometries of the remaining CHEX types are evaluated, resulting in the selection of the single best performing surface geometry for the present application.

3.1 Mathematical Formulation - Coarse Filter

A numerical rating procedure was used to select the two most compatible CHEX types for three general FCGT process conditions: Fuel Preheater, Low Temperature Gas Turbine Recuperator, and High Temperature Gas Turbine Recuperator. The criterion used to make this selection include compactness, durability, material cost, manufacturability, availability, maintenance, and applicability. Each of these criteria was given a weight factor according to its importance for each FCGT process condition. The weighting scale was defined as a range from one to five, where five carried the most importance. The weights given to each criterion for each process condition consist of the following:

1. Compactness was assigned a weight factor of five for all three FCGT process conditions.
2. Durability was assigned a weight factor of four for the Fuel Preheater and five for both Low and High Temperature Recuperators.
3. Material Cost was assigned a weight factor of three for the Fuel Preheater and Low Temperature Recuperator assuming stainless steel is used. A weight factor of five was assigned for the High Temperature Recuperator assuming a nickel alloy is used.
4. Manufacturability was assigned a weight factor of two for the Fuel Preheater and Low Temperature Recuperator assuming stainless steel is used. A weight factor of 4 was assigned to the High Temperature Recuperator assuming a nickel alloy is used.
5. Availability, maintenance, and applicability were assigned a weight factor of three for all three FCGT process conditions.

3.2 Mathematical Formulation - Fine Filter

It should be noted that vendor manufacturing characteristics (available plate and fin sizes) should be considered at this point in order to proceed in an effective manner. As illustrated subsequently in section 4.1, the BPFE and ME were chosen for further review in the present elimination step. Thus, the fine filter was performed using the plate-fin heat exchanger sizing procedure outlined by Shah [2]. This procedure requires specification of all inlet and outlet fluid properties, NTU, and all surface properties being geometrical and thermal-hydraulic. From these inputs the CHEX volume necessary to meet the prescribed heat duty can be found, in which the fine filter elimination process is based.

The High Temperature Recuperator process condition was considered in the present CHEX sizing analysis since it generally requires high effectiveness (>90%). Therefore, the control volume for the mathematical formulation was taken as the counterflow heat exchange portion of Fig. 1. For space considerations, mathematical expressions for certain terms subsequently mentioned but not shown can be found in the nomenclature section. The assumptions made in this analysis are as follows:

1. Control volume is adiabatic
2. Longitudinal conduction is negligible
3. Radiation is negligible
4. Entrance effects need not be considered

With known process conditions, surface geometries, and estimated extended surface efficiencies, initial core mass flux terms are obtained for each fluid side using:

$$G = \sqrt{\frac{2\, g_c\, \Delta p}{\left[\frac{f}{j}\,\frac{ntu}{\eta_o}\,\frac{1}{\rho}\,\Pr^{\frac{2}{3}} + 2\left(\frac{1}{\rho_o} - \frac{1}{\rho_i}\right)\right]}} \tag{1}$$

Core Reynolds numbers are then obtained using the core mass flux terms and other known variables. With known surface geometries and Colburn data, heat transfer coefficients are calculated. Depending on the type of surface geometry, a particular relationship is used to determine the fin efficiency for each exchanger side, followed by evaluating extended surface efficiencies. An initial overall heat transfer coefficient is then found based on known surface geometries and estimated values:

$$U_1 = \left(\frac{1}{\eta_{o.1}\, h_1} + \frac{1}{\eta_{o.1}\, h_{s.1}} + \frac{\frac{\alpha_1}{\alpha_2}}{\eta_{o.2}\, h_{s.2}} + \frac{\frac{\alpha_1}{\alpha_2}}{\eta_{o.2}\, h_2} \right)^{-1} \quad (2)$$

From this, the total heat transfer area on side 1 of the exchanger can be found. Given this area and known surface properties, the heat transfer area on the opposing side can be found. With the current mass velocity values the minimum free flow area can be found for each fluid side. Next, frontal area is obtained for both fluid sides. Because high effectiveness warrants counterflow orientation, both sides of the exchanger must have the same flow length. Therefore, a single frontal area must be agreed upon. It is recommended that the higher frontal area of the two fluid sides is assumed, Shah [20]. The minimum free flow area is then recalculated. Core flow length can then be obtained using parameters from either fluid side. From the estimated core length the core pressure drop can be estimated on both exchanger sides using:

$$\Delta p = \frac{G^2}{2\, g_c} \left[f \frac{4\, L}{D_h} \frac{1}{\rho} + 2 \left(\frac{1}{\rho_o} - \frac{1}{\rho_i} \right) \right] \quad (3)$$

Wall temperature effects are accounted for in the friction parameter of Eq. (3). Next, the mass flux terms are recalculated using the specified pressure drops and Eq. (3), followed by reevaluation of core Reynolds numbers and all subsequent steps described. For the second and subsequent iterations wall resistance is accounted for so that Eq. (2) becomes:

$$U_1 = \left(\frac{1}{\eta_{o.1}\, h_1} + \frac{1}{\eta_{o.1}\, h_{s.1}} + \frac{a\, A_1}{k_w\, A_w} + \frac{\frac{A_1}{A_2}}{\eta_{o.2}\, h_{s.2}} + \frac{\frac{A_1}{A_2}}{\eta_{o.2}\, h_2} \right)^{-1} \quad (4)$$

The specified and calculated pressure drops are then compared after each iteration, when they are within a desired tolerance the sizing procedure is complete. At this time the exchanger volume can be obtained, followed by thermal density.

3.3 Numerical Procedure

The commercial software Mathcad was used to carry out the fine filter numerical setup. Five surface geometries were considered: plain, louver, strip, wavy, and semicircular. The vast majority of surface information assessed with the code was taken from the extensive work of Kays and London [9]. The code remained identical for each surface analysis with exception to the heat transfer and friction characteristics unique to the given surface, which also bears distinct values for the following surface properties: hydraulic diameter, compactness, fin pitch, plate spacing, fin thickness, fin area per total area, and fin length. Optimization attempts such as using multiple fin layers or cross corrugated wavy patterns were ignored in this comparison. The fin layer for both hot and cold fluid sides was assigned identical. In general, this configuration would not yield a practical CHEX design, but this technique will show the thermal density of a particular surface geometry relative to another, given the present process condition. Eight iterations were carried out for each surface analyzed to obtain a consistent high level of convergence.

3.4 Code Validation

The numerical code was validated by reproducing data published by Wang [21], data of which was originally produced by Concepts Northern Research & Energy Corporation (Concepts NREC). This analysis sized a PCHE for a high temperature (helium) gas turbine recuperator, where multiple core and header dimensions (thus multiple pressure drops) were considered. The present numerical sizing procedure produced core dimensions that correlate well with the published data. Fig. 2 is a plot of PCHE thermal density (including distributor volume) versus header width. Discrepancy between the published and calculated data is also shown on Fig. 2 via the dashed lines, which lie roughly between 1.5 – 2.0 percent error.

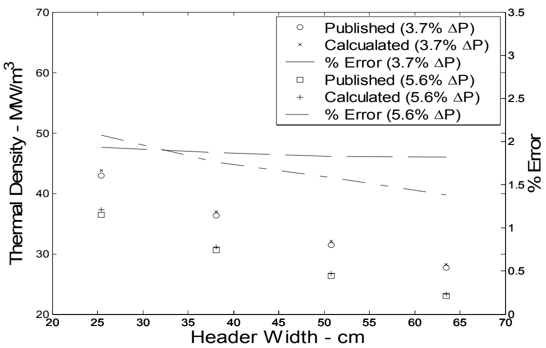

Fig. 2. Code Validation, TD versus Header Width

4. Results and Discussions

The results of the current study are divided into two categories, namely the coarse filter and fine filter. In the former case the heat exchangers are rated by using a set of predetermined design criteria such as compactness, durability, materials cost, etc. In the latter case, the performance of the heat exchangers is evaluated based on the heat transfer and fluid flow characteristics of the given surface of construction.

4.1 Coarse Filter

Each CHEX received a performance rating for each process condition and criterion. The rating scale was defined as a range from one to ten, where ten was the best score. Justification of the ratings given are the following:

1. With exception to the FTE, compactness ratings for all FCGT process conditions were directly proportional to the compactness data in Table 1. FTE ratings were effected by the expected flow orientation.
2. Durability ratings were assigned according to a CHEX's potential to overcome creep and fatigue. The assumptions made were as follows:
   - The BPFE can facilitate non-monolithic clamping as well as diffusion bonding.
   - The FTE can have problems with tube vibrations.
   - Diffusion bonding is used for ME assembly.
   - PSE durability decreases greatly above 650°C.
   - The SE is currently under investigation based in part on its rugged durability.
3. Material Cost ratings were assigned based on the cost of raw material necessary to transfer a unit of heat. The assumptions made were as follows:
   - Required material stock is relatively inversely proportional to compactness.
   - The FTE requires more expensive tube stock and its assembly can result in excessive material waste.
   - The ME requires relatively thick sheet stock for the flow channel etching process.
4. Manufacturability ratings were assigned based on the difficulties posed in fabrication. The assumptions made were as follows:
   - The BPFE and FTE have offsetting characteristics of high parts count and relatively inexpensive fabrication due to a long production history.
   - The ME has relatively expensive fabrication due to a short production history and sophisticated assembly.
   - The PSE and SE require significant investment in preload machinery.
5. Availability ratings were assigned based on market status. The assumptions made were as follows:
   - Competitive markets exist for The BPFE and FTE.
   - Nominal markets exist for the ME, PSE and SE.
6. With exception to the SE, Maintenance ratings were rated inversely proportional to Compactness data.
7. Applicability ratings were assigned based on CHEX attributes pertinent to the FCGT application. The assumptions made were as follows:
   - Ingersoll-Rand designed a BPFE in part for the FCGT application [22].
   - The FTE is better suited for gas-liquid or high pressure ratio applications.
   - The ME holds much promise for increased CHEX performance.
   - Most PSE designs were designed for high pressure ratio engines with operating temperatures at or below 650°C.
   - Low compactness SE designs may not be conducive with the inherently low power density, high temperature fuel cell stacks.

Total scores were tallied for each CHEX type for each process condition by summing the products of corresponding weights and ratings, see Tables 2-4.

Table 2 indicates the two best CHEXs for the Fuel Preheater process condition are the ME and BPFE, having a total score of 173 and 170, respectively. Despite the option of crossflow for the Fuel Preheater, it was not enough to make the FTE competitive. Similarly, the greatest attributes of the PSE and SE are durability, a less important criterion for the FCGT application.

Table 2. Fuel Preheater Selection

	Weight	BPFE	FTE	ME	PSE	SE
Compactness	5	7	3	10	4	2
Durability	4	8	8	10	10	10
Material Cost	3	8	4	9	10	6
Manufacturability	2	8	8	4	7	7
Availability	3	10	10	5	5	5
Maintenance	3	3	9	1	6	10
Applicability	3	10	5	10	7	8
	Total	**170**	**147**	**173**	**158**	**151**

Table 3 indicates the two best rated CHEXs for the Low Temperature Recuperator are the ME and BPFE, having a total score of 183 and 178, respectively. The FTE was rated even lower for this process condition given that high effectiveness is expected. The increase in durability requirements shortened the margin between the BPFE and the PSE, but not enough to offset emphasis on compactness.

Table 3. Low Temperature Recuperator

	Weight	BPFE	FTE	ME	PSE	SE
Compactness	5	7	1	10	4	2
Durability	5	8	8	10	10	10
Material Cost	3	8	4	9	10	6
Manufacturability	2	8	8	4	7	7
Availability	3	10	10	5	5	5
Maintenance	3	3	9	1	6	10
Applicability	3	10	5	10	7	8
	Total	**178**	**145**	**183**	**168**	**161**

Table 4 indicates the two best rated CHEXs for the High Temperature Recuperator process condition are the ME and BPFE, having a total score of 204 and 201, respectively. The margin at which the ME and BPFE are rated over the other CHEXs for this process condition is much greater than when stainless steel is the material of construction. This implies that the compactness criterion

Table 4. High Temperature Recuperator

	Weight	BPFE	FTE	ME	PSE	SE
Compactness	5	7	1	10	4	2
Durability	5	8	8	10	5	10
Material Cost	5	7	1	8	10	5
Manufacturability	4	8	8	4	7	7
Availability	3	10	10	5	5	5
Maintenance	3	3	9	1	6	10
Applicability	3	10	5	10	7	8
	Total	**201**	**154**	**204**	**177**	**182**

has a compounding effect when expensive alloys are used. In summary, the two CHEX types to be analyzed further in the fine filter selection process are the BPFE and ME.

4.2 Fine Filter

The thermal density of the counterflow CHEXs constructed out of the various fin geometries mentioned previously were plotted against their respective compactness values as shown in Figs. 3-6. It was taken from Figs. 3-5 that thermal density exhibits a relatively linear relationship with compactness. To determine the strength of this relationship, a squared correlation coefficient (r^2) was evaluated for each curve fit. The plain fin curve fit exhibited an r^2 value of 0.971, the louver fin curve fit a value of 0.904, and the strip fin curve fit a value of 0.872. It was assumed that these relationships could be extrapolated for a reasonable range of compactness values; hence, Fig. 6 presents a comparison of the general surface geometry performance correlations. There was enough data in the literature to obtain reasonable curve fits for the plain, louver, and strip fin geometries. However, this work is currently in progress and a sufficient amount of data for the wavy and semicircular geometries is yet to be obtained. Therefore, Fig. 6 has individual wavy and semicircular data points plotted with the plain, louver, and strip fin representations.

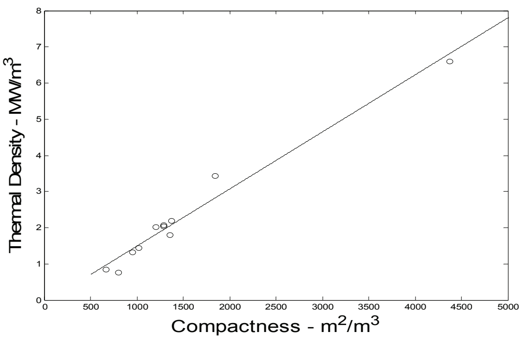

Fig. 3. Plain Fin TD versus β

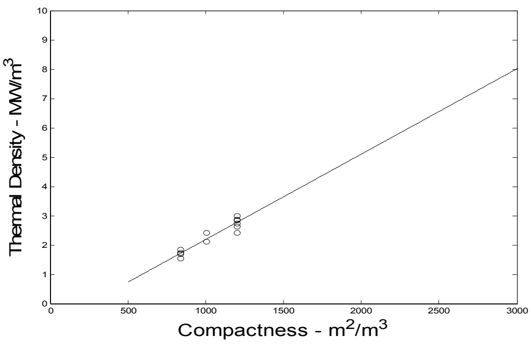

Fig. 4. Louver Fin TD versus β

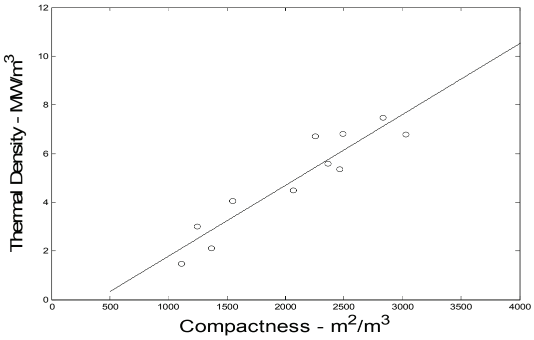

Fig. 5. Strip Fin TD versus β

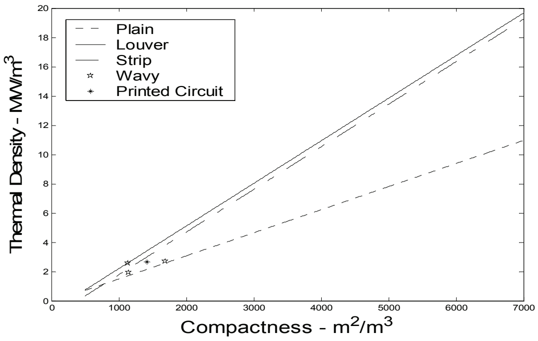

Fig. 6. Fin Comparison, TD versus β

Figs. 3-6 demonstrate the trivial concept that CHEX thermal density increases with increased compactness. More importantly, the results indicate which surface geometry will yield the highest thermal density for a given level of compactness. This is the basis for the fine filter elimination procedure. Fig. 6 indicates that the louver and strip fin geometries are very competitive, and that both of these surfaces clearly yield higher thermal density than the plain fin geometry for increased compactness. This figure also implies that the louver fin is superior to the strip fin for the present process condition.

It was assumed that the wavy and semicircular geometries also exhibit a linear relationship between thermal density and compactness, having a slope commensurate to that of the louver and strip fin geometry. If this assumption remains valid, then even the small amount of data in Fig. 6 implies that the louver fin generally yields the highest thermal density, or smallest core volume for a prescribed heat duty, of all surface geometries considered for the present process condition.

In addition to the numerical results, the louver fin geometry has other desirable characteristics. The louver fin is formed by a relatively inexpensive rolling process, instead of by a reciprocating press necessary for the strip fin, which makes it much cheaper to produce, Hesselgreaves [14]. Therefore, the louver fin surface geometry is currently found to be most compatible with hybrid FCGT process conditions.

5. Conclusion

Based on the literature review and coarse filter performed for this work, plate-fin and microchannel CHEXs were determined to have the most potential to meet the requirements placed forth by hybrid FCGT systems. To continue performance improvements in recuperator design, ability to increase cell compactness must remain. The plate-fin and microchannel have an advantage over competing CHEXs with respect to achieving high compactness.

Durability has been a recurring issue for gas turbine recuperators. However, it was concluded that both the plate-fin and microchannel designs have more than sufficient potential to successfully endure the structural demands expected from the present application. It was concluded that the primary concerns for FCGT system recuperators lie within their size and cost, especially for high temperature (>650°C) process conditions. Commercial availability will also play a crucial role for high temperature operation. If market conditions permit choice, then the results from this analysis indicate that a plate-fin heat exchanger constructed with a compact louver fin geometry is the most promising configuration for the hybrid FCGT process conditions.

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